COMPARISON OF GENERAL PERTURBATIONS

AND SPECIAL PERTUBATIONS EPHEMERIDES

JUNE 1966

E. H. Larson
J. B. Frazer

Prepared for

SYSTEM PROGRAM OFFICE (496L/474L)
SURVEILLANCE & CONTROL SYSTEMS
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L. G. Hanscom Field, Bedford, Massachusetts

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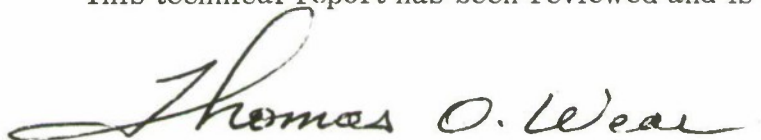
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ABSTRACT

The accuracy of the SPACETRACK General Perturbations program over short periods is evaluated for a number of cases. They show that oscillatory terms resulting from drag perturbations contribute heavily to errors at low altitudes, and that these terms must be eliminated if the first order theory is to be used for high accuracy in these circumstances. It appears that the evaluation technique employed would be useful in addressing a number of other problems; several promising applications are discussed.

REVIEW AND APPROVAL

This technical report has been reviewed and is approved.

THOMAS O. WEAR, Colonel, USAF
Director, 496L/474L System Program Office
Deputy for Surveillance & Control Systems

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GLOSSARY

A	cross-sectional area
a	semimajor axis
C_D	drag coefficient
e	eccentricity
H	atmospheric scale height
h	perigee in distance above earth's surface
L	mean longitude
m	mass of satellite
$\frac{1}{2}\dot{n}$	$\frac{1}{2}$ rate of change of mean motion
P	period
q	perigee in distance from center of earth
t	time since epoch
v	velocity of satellite with respect to air mass
β	ballistic coefficient
ρ	atmospheric density
ρ_o	atmospheric density at perigee
χ	dimensionless drag parameter $= \rho_o\, \beta\, q$

SECTION I

INTRODUCTION

In the SPACETRACK System, it is customary to use a special pertur-
bations program* when a high degree of accuracy is desired over a short
interval of time. The purpose of this investigation is to determine whether
and under what circumstances a first order general perturbations program**
may be used instead; and if possible, determine whether any modifications
to it are feasible. The interval of time considered in this study is of the
order of 1-1/2 days, and thus interest is in accuracy of the order of 1 km.
Most of the study deals with low altitudes since drag is the perturbative
force.

There already was in existence before the start of this investigation a
program called DCMOD64, written by the Aeronutronic Division of the Philco
Corporation, well suited for the purpose of making comparisons. In fact,
without this program's prior existence, it would have been impossible to
finish this study in a reasonable time. Other investigators have already used
this program for similar studies.[1] In this study, we are concerned with a
shorter period for the approximation interval and higher accuracies.

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* A program in which the effects of the perturbing forces are numerically
integrated.

** A program which employs an analytic theory of the effects of perturbing
forces.

SECTION II

DESCRIPTION OF COMPUTER PROGRAM

The DCMOD64 program[2] includes an orbital element correction routine, and several ephemeris computation subroutines. We have used a special option of this program for our study. In this option, the special perturbations subroutine generates an ephemeris from an initial set of orbital elements. This is then converted into 400 equally spaced (in time) observations from a hypothetical radar with spherical coverage. Then the general perturbations subroutine is used in the element correction routine to fit these observations. The final output is a table of discrepancies between the special and general perturbations ephemerides. The first order general perturbations theory is equivalent to Lyddane's modification of the Brouwer theory; it should achieve precisions on the order of 1 part in 10^6, or 1 microradian, over 10^3 radians of satellite motion, insofar as perturbations due to the earth's potential are concerned. Only the 3 largest zonal harmonics, $J_2 - J_4$, are included in the formulation. The subroutine also includes a formulation for the perturbative effects of solar radiation pressure, which were of little significance in this study. Other perturbations, of which air drag is the most significant, are accommodated by two empirical terms in the mean anomaly equation, $\dot{n}/2$ and $\ddot{n}/6$, so that a correction to the mean anomaly is given in the form

$$\delta M = \frac{1}{2} \dot{n} \, t^2 + \frac{1}{6} \ddot{n} \, t^3 \quad ,$$

where t is time since epoch.

Related corrections to the semimajor axis and the eccentricity are derived from these parameters under the assumption of constant perigee height. The special perturbation subroutine that generates the ephemeris takes into account

eight zonal harmonics, four tesseral harmonics, atmospheric drag, solar radiation pressure, and lunar and solar gravitational perturbations. It is possible to omit any or all of these in any run. The atmosphere model takes into account the diurnal bulge as well as solar activity, but these are not effective at the altitudes chosen for this study. The ballistic coefficient, β, is assumed constant. For the puspose of this study, it was necessary to modify the DCMOD program with octal corrections to make the time period 36 hours.[*]

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SECTION III

DESCRIPTION OF CASES

Several different classes of satellites were simulated. All were specified by their initial osculating elements. All had an initial inclination of 49 degrees. Initial perigees used were:

h (km)	h (km)
160	87.7
200	109.6
250	137.0
300	164.4

These were used in combination with initial eccentricities of:

0.0
0.001
0.01
0.1
0.2
0.3

Various combinations of the perigees and eccentricities were used in the program under three different classes of perturbations in the special perturbations program:

(a) all perturbations;

(b) only second, third, and fourth zonal harmonics of earth's potential; and

(c) only atmospheric drag and second, third, and fourth zonal harmonics of earth's potential.

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It was originally intended that all satellites have the same ballistic coefficient, β . The value 0.02 m^2/kg was tried, since this appears to be a high average,[3] and results using this value should be conservative. However, for some low-altitude satellites with small eccentricities, the special perturbations subroutine would not run 36 hours with this value, presumably because of decay, and so the smaller values listed in the tables were used in these cases.

SECTION IV

SUMMARY OF RESULTS

Thirty-six different cases were run; the results are summarized in Tables I, II, and III. Each of these tables presents the distinguishing initial conditions followed by columns containing five mean parameters determined by AGP;[*] viz, h (computed perigee), e (eccentricity), a (semimajor axis), P (period), and $\dot{n}/2$ (rate of change of mean motion). These are followed by the errors in 36 hours of simulated time. The RMS error is the root mean square of all 400 error vector magnitudes in the 36-hour period. The maximum error is the maximum magnitude of the 400 vector errors in the same time period.

Table I contains the cases wherein all perturbations are included. Table II presents the cases wherein the only perturbations are the 2nd, 3rd, and 4th zonal harmonic terms of the earth's potential. Table III, which presents the cases in which the only perturbations are atmospheric drag and the oblate earth terms, contains two additional columns, the first of which is adjusted RMS errors. These are the RMS values adjusted by multiplying the factor $0.02/\beta$. This is done to facilitate comparison of results for different cases since, presumably, errors are roughly proportional to the ballistic coefficient. The figures in the other additional column are normalized RMS errors. These are nondimensional quantities consisting of the RMS error value divided by the quantity $(a\chi/e)$, where $\chi = \rho_o \beta q$ is a nondimensional parameter which gives the order of magnitude of the errors due to atmospheric drag. A fuller discussion of these quantities is presented later.

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[*] AGP is the acronym of the general perturbations routine designed for non-equatorial cases.

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TABLE I

Errors in Approximating Ephemris by General Perturbations – (All perturbations included)

Job Number	Satellite Number	Initial Osculating Elements			Mean Parameters					Errors in 36 Hrs.	
		h_0 (km)	e_0	B (m²/kg)	h (km)	e	a (earth radii)	P (minutes)	$\frac{\dot{n}}{2} \times 10^{10}$ (per min²)	RMS (m)	Max. (m)
103	3	160	0	.001	146.1	.001853	1.023967	87.535	294.5	2,568	10,900
104	4	160	.001	.002	162.0	.001434	1.024969	87.663	352.8	3,566	13,700
105	5	160	.01	.02	152.5	.009824	1.034056	88.832	822.5	6,952	30,200
106	6	160	.1	.02	158.9	.099078	1.137627	102.508	385.1	324	1,320
167	17	300	0	.02	289.6	.001277	1.045942	90.368	36.6	400	1,980
168	18	300	.001	.02	294.1	.000843	1.046989	90.504	32.1	381	1,600
169	19	300	.01	.02	298.9	.009130	1.056498	91.740	15.4	291	1,340
170	20	300	.1	.02	299.0	.099104	1.162047	105.827	5.2	217	952

TABLE II

Errors in Approximating Ephemris by General Perturbations - (Only 2nd, 3rd, and 4th zonal harmonic perturbations included)

Job Number	Satellite Number	Initial Osculating Elements			Mean Parameters					Errors in 36 Hrs.	
		h_o (km)	e_o	B (m²/kg)	h (km)	e	a (earth radii)	P (minutes)	$\frac{\dot{n}}{2} \times 10^{10}$ (per min²)	RMS (m)	Max. (m)
113	3	160	0	.001	149.6	.001234	1.023952	87.533	-.0773	29	122
114	4	160	.001	.002	154.2	.000788	1.024976	87.664	-.0351	71	302
115	5	160	.01	.02	158.8	.009091	1.034286	88.861	-.0587	68	308
116	6	160	.1	.02	159.0	.099057	1.137605	102.506	.0181	20	66
117	7	200	0	.015	189.7	.001223	1.030230	88.339	.0256	28	110
118	8	200	.001	.02	194.2	.000782	1.031261	88.472	-.0516	27	106
119	9	200	.01	.02	198.9	.009092	1.040627	89.680	.0338	27	91
120	10	200	.1	.02	199.0	.099068	1.144586	103.450	-.0187	20	70
121	11	200	.2	.02	198.9	.199068	1.287491	123.419	-.0173	16	54
122	12	200	.5	.02	198.9	.499051	2.058460	249.515	.0096	18	55

TABLE III

Errors in Approximating Ephemris by General Perturbations – (Only atmospheric and 2nd, 3rd, and 4th zonal harmonic perturbations included)

Job Number	Satellite Number	Initial Osculating Elements h_o (km)	e_o	B (m²/kg)	Mean Parameters h (km)	e	a (earth radii)	P (minutes)	$\frac{\dot{N}}{2} \times 10^{10}$ (per min²)	Errors in 36 Hours RMS (m)	Max. (m)	Adjusted RMS (m)	Normalized RMS = RMS/2N × 100
123	3	160	0	.001	146.1	.001858	1.023951	87.532	295.3	2,534	10,600	50,780	4.82
124	4	160	.001	.002	162.0	.001409	1.024952	87.661	352.8	3,518	13,400	35,180	5.40
125	5	160	.01	.02	150.3	.010044	1.033947	88.818	685.1	9,177	38,400	9,177	5.92
126	6	160	.1	.02	158.9	.099068	1.137611	102.506	386.6	245	1,250	245	2.11
127	7	200	0	.015	181.7	.002057	1.030006	88.310	291.0	6,585	26,700	8,780	3.77
128	8	200	.001	.02	201.4	.001191	1.031037	88.443	319.8	5,646	23,700	5,646	2.43
129	9	200	.01	.02	197.9	.009234	1.040630	89.680	258.5	585	2,420	585	1.76
130	10	200	.1	.02	198.9	.099071	1.144586	103.451	77.84	62	301	62	1.88
131	11	200	.2	.02	198.9	.199069	1.287491	123.419	49.87	39	199	39	2.09
132	12	200	.5	.02	198.9	.499051	2.058461	249.515	17.48	24	80	24	2.00
213	13	250	0	.02	237.2	.001559	1.038083	89.351	162.3	1,195	5,200	1,195	1.60
214	14	250	.001	.02	254.9	.001015	1.039120	89.485	131.2	990	5,340	990	1.27
215	15	250	.01	.02	248.7	.009138	1.048555	90.707	53.42	148	671	148	1.49
216	16	250	.1	.02	249.0	.099083	1.153307	104.635	16.21	28	106	28	2.76
217	17	300	0	.02	289.4	.001269	1.045927	90.366	37.06	259	999	259	.82
218	18	300	.001	.02	294.1	.000827	1.046973	90.501	31.72	225	1,160	225	.52
219	19	300	.01	.02	298.8	.009128	1.056482	91.737	19.93	58	246	58	1.58
220	20	300	.1	.02	299.0	.099096	1.162027	105.824	4.22	21	77	21	5.81

A point of interest that does not appear in these tables is the nature of the error as a function of time, or alternatively, as a function of true agrument of latitude. Generally speaking, in the cases in which only atmospheric and zonal harmonic perturbations are considered, the out-of-plane component is an order of magnitude smaller than the other two components. Both the along-track and radial components have a decidedly oscillatory behavior, with maximum amplitude at the ends of the simulation interval and a phase change near the center of the interval. Figure 1 shows the three components of the error as a function of observation number, which is proportional to time, for job 213, which may be regarded as archetypical of the runs in Table III.
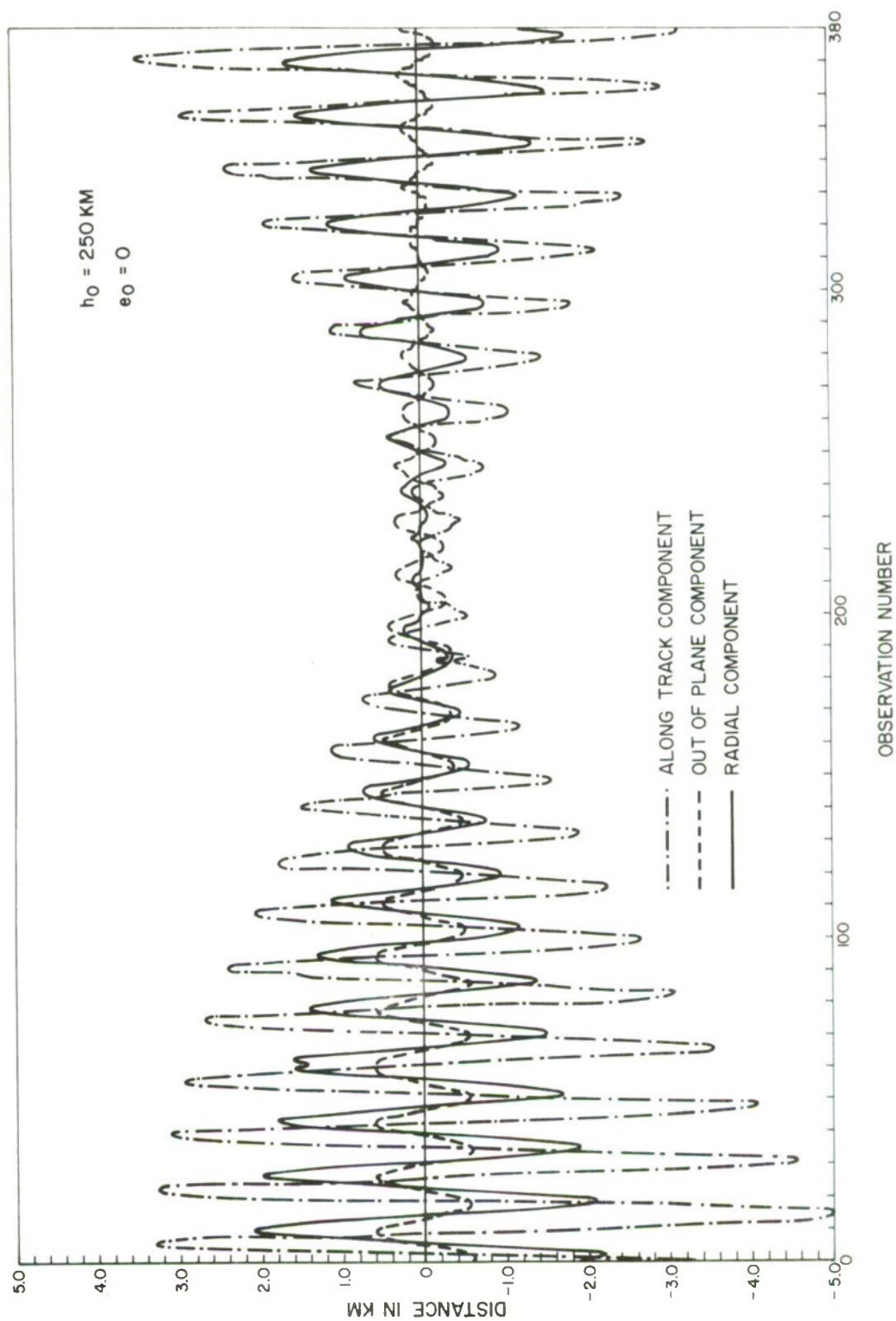
Figure 1. Vector Errors in Approximating Ephemeris by General Perturbations for Job 213

SECTION V

DISCUSSION OF RESULTS

GENERAL

The runs in Table I were made primarily to determine regions wherein
the first-order general perturbations theory is adequate by comparison with
the best available model of the real world. They clearly show that for satel-
lites with a 160-km perigee, the theory will give errors much larger than
1 km for eccentricities less than 0.01. A comparison with the cases in
Table III at this same perigee shows a very high correlation. This strongly
suggests that, at this perigee, the oblate earth and atmospheric perturbations
are the only ones which are significant for short periods. This was the reason
for confining the rest of the study to an examination of drag effects. A com-
parison of the data at the 300-km perigee shows a much poorer correlation —
other perturbations are much more significant in proportion — but the others
would still be small enough to be acceptable if the drag errors could be
eliminated. In general, the data in Table I suggest that the existing first-
order theory is adequate for any altitude above 350 km.

The runs in Table II, with only J_2 - J_4 zonal harmonic perturbations,
were intended to provide a comparison for the runs in Table III which has
atmospheric drag as well as the J_2 - J_4 zonal harmonic perturbations.
Since the first-order theory accounts for these zonal harmonic perturbations,
the errors should be on the order of 6 to 18 meters for all Table II cases.
The reason they are not zero is not entirely clear.

Part of the difference arises from the fact that the J_2 - J_4 values
stored in the special and general perturbations subroutines do not agree.
This disagreement arises because the special perturbations set, with

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12 parameters, and the general perturbations set, with 3 parameters, have been independently adjusted for a best fit with the observed motion of satellities. This discrepancy was not discovered sufficiently early in the study for corrective measures to be taken. As a check on the significance of the discrepancy, job 115 was rerun. The maximum error was reduced from 308 meters to 18 meters, while the RMS error was reduced from 68 meters to 6.8 meters. The oscillatory pattern of the errors remains, but there is no apparent tendency for the amplitude of the oscillation to grow with time.

A second phenomens is evident in Table II: the errors grow with decreasing eccentricity. It is possible that this is due to the discrepancy in the J_2 - J_4 terms; on the other hand, it may reflect numerical problems in the element correction process.

The convergence of the solutions appeared to be rather slow in all cases; from 6 to 8 Phase II* iterations were usually required for convergence to a 1-percent change in the RMS of the vector magnitudes.

DRAG EFFECTS

Table III presents the errors in runs with drag perturbations as well as the J_2 - J_4 zonal harmonics. Since the general perturbations subroutines account for the harmonics with the accuracies given in Table II, the additional errors in these cases must be due to drag alone or to cross-coupling between drag and zonal harmonics. The magnitude of the acceleration of a satellite due to drag is given by

$$\frac{1}{2} \rho v^2 \beta \quad ,$$

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* In Phase I, only the mean anomaly or "time" equation is corrected; in Phase II, all elements are corrected.

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where ρ is the density, v is the velocity with respect to the air mass, and β , the ballistic coefficient, is given by

$$\beta = C_D A/m ,$$

where C_D is the drag coefficient, A is the cross-sectional area of the satellite, and m is its mass.

In general, as a satellite rotates, neither C_D nor A remains constant so that β varies with the orientation. However, for satellites in which the ratio of the longest to shortest dimension is no larger than two or three, the product does not vary very much, and, for a given satellite, β varies perhaps by 20 percent or less.[4]* However, β does vary considerably from one satellite to another because of differences of mass. The value of 0.02 m^2/kg used in the simulation is conservative in that few satellites could be expected to have a larger value.

Air density, ρ , decreases quite rapidly with altitude. For altitudes between 160 and 300 km, the scale height, H , given by

$$H = -\rho\Big/\frac{d\rho}{dZ} ,$$

is of the order of 25 to 50 km.[5]

Since perigee does not change very rapidly for satellites above 200 km, a useful dimensionless parameter that given the scale of perturbations is

$$\chi = \rho_o \beta q ,$$

where ρ_o is density at perigee, q .

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* Pages 12 to 17.

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The last column of Table III shows a definite correlation between RMS errors and $a\chi/e$. The reason for the inverse variation of the RMS errors with eccentricity is not known. Quite possibly the problem will prove to be identical to that in the nondrag cases of Table II; the amplitude and growth of the oscillations, however, is substantially greater.

In an analysis in terms of coordinates, Geyling[6] obtained terms similar to this. His factor of proportionality does not appear to vary inversely as the eccentricity; perhaps this is because his atmospheric density model is independent of altitude. Analysis along these lines, using a more realistic density model, might show results similar to those obtained here, although, at best, preliminary analysis has shown a variation inversely as the square root of the eccentricity.

SECTION VI

CONCLUSIONS

The techniques employed for this study have considerable potential for
studying the performance of the DCMOD64 element correction routines. The
rather slow convergence and possible poor performance for low eccentricity
deserve further study. Other areas of interest include the dependence of
quality of fit on amount of data and length of arc. By using an identical
ephemeris subroutine for data generation and fitting, it is possible to check
numerical and partial derivative problems. By using special and general
perturbations routines with identical harmonics, it is possible to crosscheck
the mathematical formulations, to determine the intervals over which the
routines remain valid and to determine what length of fit is necessary to
prevent second order terms in the semimajor axis from propagating into
the mean motion. By using the full set of harmonics in the special pertur-
bations subroutine and the $J_2 - J_4$ set in the general perturbations sub-
routine, the need for additional general perturbations formulations can be
assessed.

Similar tests can be made for the tesserals and drag perturbations. In
the case of drag perturbations, it may well be the optimal procedure to
develop additional general perturbations formulations based on an empirical
analysis of the periodic residuals (for periodic terms), and on the analysis of
mean elements for overlapping arcs (for secular terms). Among the more
obvious questions that can be resolved by such techniques are the extent of
gravitational drag cross-coupling in the motion of node and perigee, and
the secular behavior of eccentricity.

For greater consistency and to avoid errors in using subsets of the full
potential model, it is suggested that the DCMOD64 control logic for the

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special perturbations subroutine be modified to permit selection of optimized subsets of the zonal and tesseral harmonics, rather than selective inclusion or deletion of individual harmonics. Based on reports in the literature of the techniques used to determine the harmonics, it is probably possible to treat even zonals, odd zonals, low-order tesserals $(n \leq 8)$, and high-order tesserals $(n \geq 13)$ as four independently optimized subjects. Suggested options would include the general perturbations subroutine values of $J_2 - J_4$, the current full set of zonals $(J_2 - J_9$ or $J_2 - J_{14})$, and the full set of zonal harmonics plus all available tesserals.

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14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.